Modeling and Analyzing the Propagation of Uncertainty

Michael B. Porter
Science Applications International Corp.
10260 Campus Point Drive, San Diego, CA 92121
phone: (858) 826-6720 fax: (858) 826-2700 email: michael.b.porter@saic.com

Paul Hursky
Science Applications International Corp.
10260 Campus Point Drive, San Diego, CA 92121
phone: (858) 826-6149 fax: (858) 826-2700 email: paul.hursky@saic.com

T. Martin Siderius
Science Applications International Corp.
10260 Campus Point Drive, San Diego, CA 92121
phone: (858) 826-7055 fax: (858) 826-2700 email: thomas.martin.siderius@saic.com

Award Number: N00014-00-D-0115

LONG-TERM GOALS

To develop techniques and/or models that provide error bars on relevant SONAR predictions (e.g. "range-of-the-day"). Furthermore, to develop procedures for reducing the uncertainty in those resulting predictions using readily available, through-the-sensor data.

OBJECTIVES

Shallow-water environments have become increasingly important for naval operations. Unfortunately, these regions are also characterized by ocean variability and, due to typically downward-refracting conditions, an increased sensitivity to bottom properties. Of course, bottom properties are also often poorly known, especially in shallow water. As a result, there is a lot of concern about 1) how to improve our knowledge of the variability in the waveguide and 2) how to provide error bars for predicted transmission losses, so Navy operators have an indication of their reliability. The goal of this work is to address both these issues. Note that variability in this discussion refers to both temporal and spatial changes.

APPROACH

We have followed a two-prong approach in our work. First, we are exploring a technique (adjoint modeling) that is currently an active area of research in oceanography but is completely new to analyzing uncertainty in ocean acoustic propagation. Second, we are developing new versions of popular acoustic models that can provide rapid field calculations for ensembles of ocean environments.

The adjoint approach in oceanography addresses the problem of understanding where environmental errors in the initial conditions and forcing are causing errors in the resulting nowcasts. Thus one can run an ocean circulation model with a given initialization and wind forcing forward in time. At the end

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2003**	2. REPORT TYPE	3. DATES COVERED **00-00-2003 to 00-00-2003**

4. TITLE AND SUBTITLE **Modeling and Analyzing the Propagation of Uncertainty**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Science Applications International Corp.,,10260 Campus Point Drive,,San Diego,,CA,92121**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**8**	

of the simulation one then performs environmental measurements, e.g., XBT's to compare the true ocean state with that predicted by the forward model. One then derives a reverse ocean circulation model (the adjoint) that can be run backwards in time to see how those errors were caused by earlier errors in the initial conditions or forcing. It turns out that there is a nice analogy between this ocean weather forecast problem and the one critical for an acoustic forecast, which we pursue to develop a similar way of analyzing uncertainty in the acoustic environment.

The second problem is to provide error bars alongside acoustic predictions of TL or the complex acoustic field. An obvious approach is simply to do Monte Carlo simulations with an ensemble of possible environments. However, this becomes computationally expensive. The idea we have followed is to look for intermediate variables in the acoustic models that can be linearly interpolated. Thus one can run the acoustic model at the environmental endpoints, characterizing for instance the maximum and minimum possible bottom sounds speeds. All the intermediate pressure fields can then be produced through a quick interpolation.

WORK COMPLETED

To demonstrate and develop the acoustic adjoint technique, we began with a parabolic equation model, which marches an initial acoustic field forward in range. An observation system such as a TB-23 tactical towed-array observes the acoustic field and compares the results to the 'acoustic forecast'. We then derived an adjoint, which is sort of a backward parabolic equation, which propagates the observation errors back to the projector, providing a continuous indicator of the errors in ocean and bottom sound speed that caused these errors.

A simulation method was developed to predict the performance of arrays (e.g. towed arrays) in shallow water scenarios with uncertain parameters in the vicinity of the array. The purpose was to develop an efficient way to estimate how uncertainties in parameters such as seabed type might influence the minimum detectable source level.

RESULTS (ADJOINT MODELING)

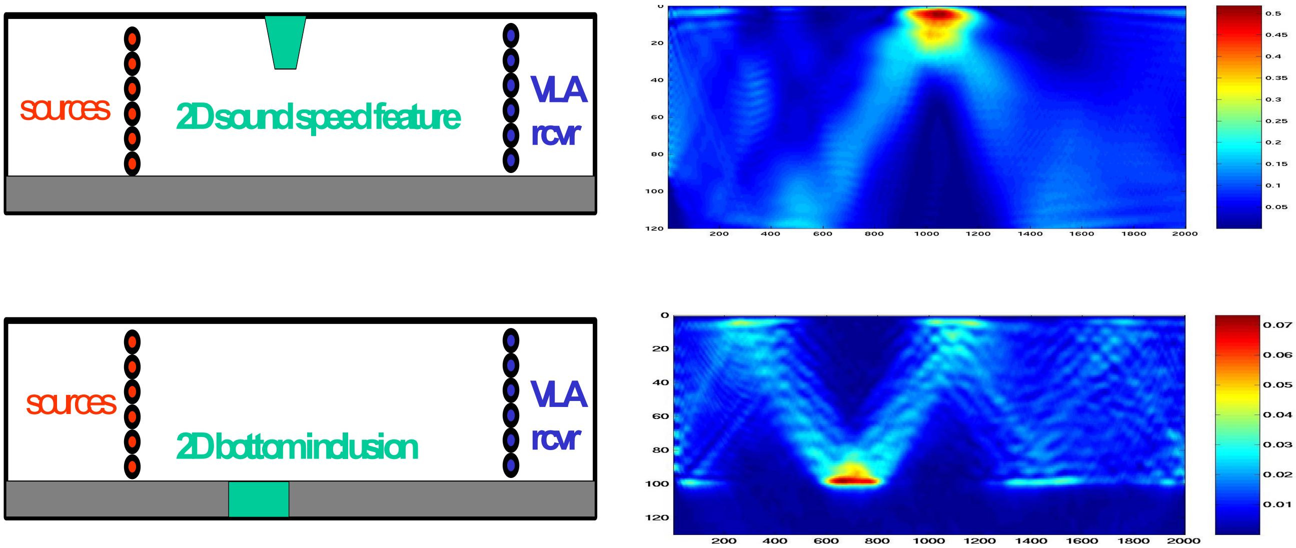

Figure 1 Two unknown range-dependent environments – which one is causing the model mismatch? Left-hand plots show configuration and location of unknown environment features causing modeling errors. Right-hand plots show how adjoint model has imaged these 2D environmental features.

We have investigated how our parabolic equation adjoint model can be used to identify the source of uncertainty in an unknown range-dependent waveguide. Recent work in acoustic inversion attests to the maturity of various techniques, but these methods presume a model has already been determined for the unknown environment. That is, these techniques vary parameters of a given model until a set of parameters is found at which model predictions reproduce the measured data. However, what if the model is not provided? What if the mismatch between measured and modeled values is due to a range-dependent water column phenomenon, and not to incorrect geo-acoustic bottom parameters? What if there is a bottom inclusion at some unknown range and having some unknown size (e.g. test case 3 from the recent workshop on geo-acoustic inversion, Ref. [1])? Under these conditions, for example, no range-independent layered bottom may be able to reproduce the measurements!

Figure 1 shows how an adjoint model calculation reveals the location of two unknown range-dependent features. The left column shows the unknown environment features (an internal wave in the upper plot, a bottom inclusion in the lower plot). The images in the right-hand panel show where in the waveguide the sound speed needs to be corrected to correct the data-model mismatch at the receive array. In the upper plot, the hot spot near the surface coincides with the solitary internal wave – adjusting the sound speed at this hot spot will correct for the model mismatch at the receive array. The lower plot shows the results of a similar calculation by our adjoint model, when the model mismatch is being caused by a bottom inclusion from 600 to 800 meters. Although the entire volume of the inclusion was not imaged, the location of the inclusion is identified by the hot spot in this figure. To fully image the bottom inclusion, the adjoint model needs to be expanded to handle density variations, in addition to the wavenumber corrections being calculated by the present model.

RESULTS (RAPID FIELD CALCULATIONS USING COUPLED NORMAL MODES)

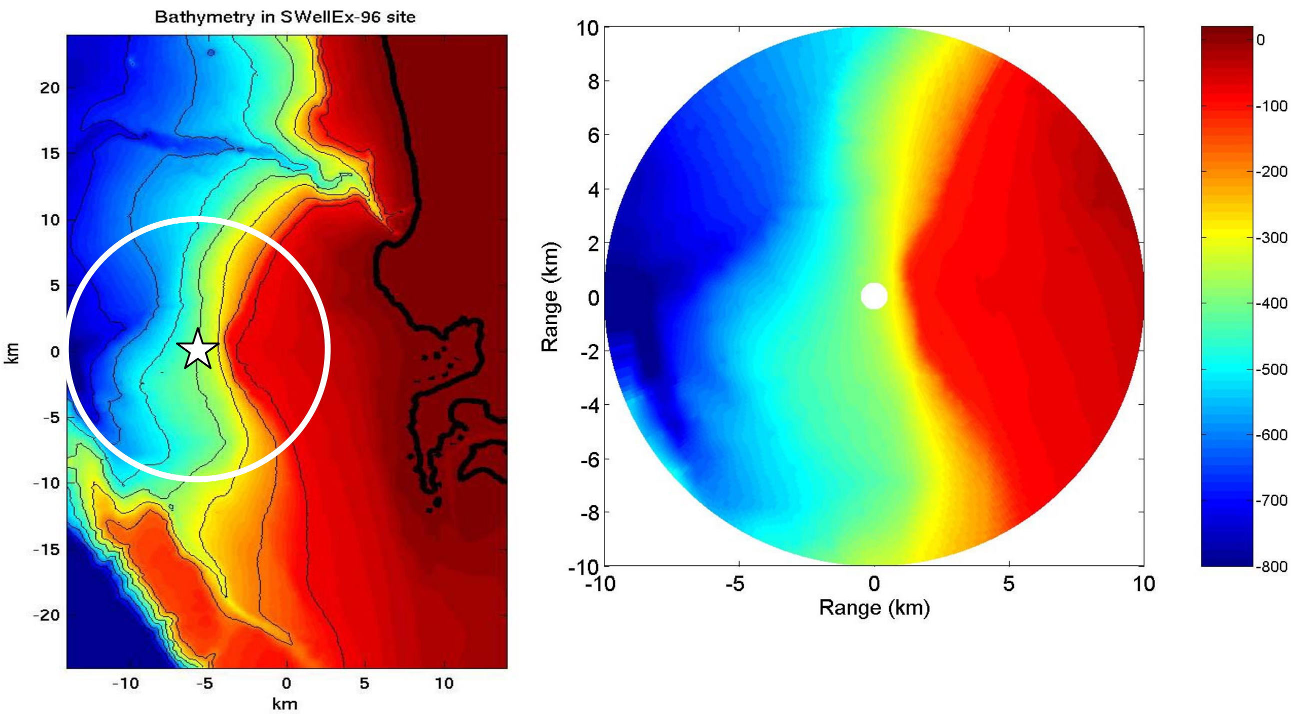

Figure 2. Left panel shows the bathymetry used to simulate array performance (from SWellEx-96) with star indicating location of towed array and the circle the area to consider for hypothetical sources. Right panel is a blow-up of the bathymetry for the 10-km region around the towed array.

An ocean acoustic modeling tool was developed this year to study uncertainty in towed array processing. A useful quantity for sonar equation modeling is the Minimum Detectable Level (MDL). This is the minimum sound level needed for detection with a specified towed array geometry, ambient noise level and detection threshold. Using propagation modeling, uncertain parameters that impact MDL can be studied for hypothetical sources that can exist anywhere in range, depth and bearing. Determining MDL uncertainty requires modeling the sound pressure fields on each element of a towed array from each hypothetical source location and this can be an overwhelming computational task. This level of detailed modeling allows true array gain to be calculated rather than simple transmission loss to the array center, which can be an important consideration for coherence on large arrays. It also allows for range dependent propagation that might vary along different bearing lines.

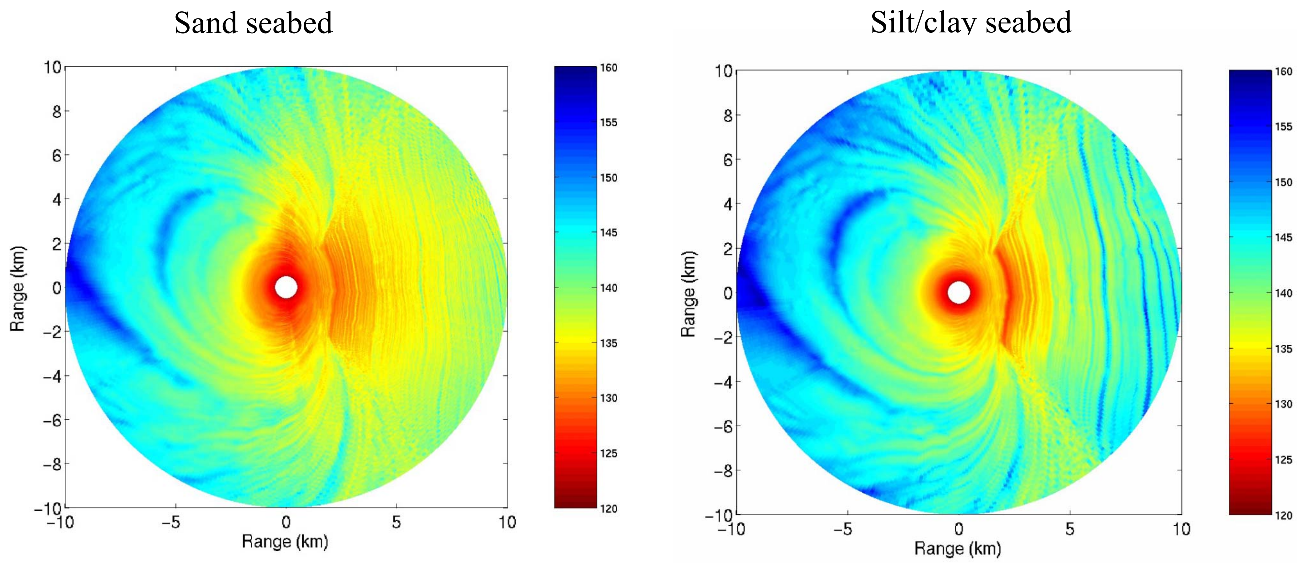

Figure 3. Left panel shows the computed minimum detectable level (MDL) in dB for a sand bottom. Right panel is the same but for a clay/silt bottom. The simulations were made at 100 Hz for a 51 element towed array with noise level of 80 dB and detection threshold of 6 dB. Using the coupled modes approach these calculations can be done rapidly to study the impact of uncertain parameters on towed array processing.

For this application a normal-mode model is particularly attractive since it can be conveniently divided into two stages: 1) a potentially burdensome pre-calculation of the normal modes for all ocean depths in the problem and their coupling matrices (which is performed only once for a given environment and 2) an extremely rapid final stage in which coupling matrices and modes are combined to calculate acoustic fields. Only the second stage needs to be repeated for different source and receiver geometries, which enables acoustic field calculations to be performed very efficiently for moving sources and receivers under various conditions and at multiple bearings. A coupled normal mode approach is used which allows range-dependent propagation to be calculated by projecting local modes onto adjacent range segments to form a coupling matrix (for details see Ref. [2]). The usual coupled mode approach projects the pressure field onto new mode sets, which are calculated on the fly as the field marches through the environment. However, when simulating arrays with a horizontal aperture, this can lead to inefficiently calculating the same quantities over and over. The approach taken here is to recognize that any variable bathymetry can be reproduced by selecting depths from a ramp of discrete canonical depths spanning the bathymetry. At each depth, the acoustic field will either propagate one step up or one step down in depth. It is only necessary to pre-calculate two coupling matrices (to step up and to step down) for each of our canonical depths, to store these in a lookup table, and to simply access this table as needed when calculating the field for a variable bathymetry. The final array response is formed by simply cascading coupling matrices according to the bathymetry for each bearing line. Since we propagate the normal mode amplitudes, rather than quantities dependent on source or receiver geometry, the field at different elements along the array is calculated with a single matrix multiply. Further, the mode functions themselves only need to be stored for locations of potential sources or receivers, and not all points in between. This is a vastly more computationally efficient way to predict array responses in three dimensions.

This type of array simulation can be illustrated using an example. Figure 2 shows an environment with range-dependent bathymetry, an array (indicated by the star), and a search area consisting of the circle centered on the array. In this example, a 51 element towed array is used (North-South orientation) at 100 Hz (array design frequency is also 100 Hz) and the water column sound speed is a typical summer, downward refracting profile.

The simulation first precomputes mode functions and coupling matrices for all water depths in the problem (right panel in Figure 2). Next, the array response is formed for hypothetical sources at all depths and ranges for each bearing and results are beamformed. The minimum detectable level is computed at all positions using an assumed noise level of 80 dB, and detection threshold of 6 dB. Since MDL will vary over depth, an average MDL over depth was used to form the MDL plots shown in Figure 3. This figure illustrates not only the impact of bathymetry on MDL, but also the relationship between bathymetry and seabed type. The areas with shallow water allow a trapping of energy and generally longer-range propagation. The left panel in Figure 3 shows the MDL for a sand bottom. The right panel shows MDL for a silt/clay bottom. Silt/clay is less reflective and thus is less favorable for long-range propagation. As a result, higher sound levels are needed for detection. Such simulations can be used to determine bounds and uncertainties in MDL due to variations in seabed type, array geometry (depth, length, orientation), and water-column sound speed profile.

IMPACT/APPLICATIONS

As described in the Objectives section, this work is producing valuable techniques for both analyzing uncertainty in a scientific setting and also for predicting the effects of uncertainty for SONAR operators. We have also been applying these techniques in a system designed to predict the performance of Navy SONAR systems on marine mammals.

RELATED PROJECTS

This work is being performed in association with researchers at Scripps Institution of Oceanography, Duke University, and Orincon, whose annual reports are part of this volume. As mentioned above, related work is also being performed in connection with the Effects of Sound on the Marine Environment (ESME) program, which also has a need for associating error bars with threshold levels for mammal exposure to sound.

REFERENCES

[1] N. R. Chapman, S. Chin-Bing, D. King, and R. B. Evans, “Benchmarking Geoacoustic Inversion Methods for Range-Dependent Waveguides”, IEEE Journal of Oceanic Engineering, Special Issue on Geoacoustic Inversion In Range-Dependent Shallow Water Environments, Vol. 28, No. 3, pp. 320-330, July 2003.

[2] F. B. Jensen, W. A. Kuperman, M. B. Porter and H. Schmidt, “Computational Ocean Acoustics”, American Institute of Physics, Inc., New York, 1994.

PUBLICATIONS

[1] P. Hursky, Michael B. Porter, Bruce D. Cornuelle, W. S. Hodgkiss, and W. A. Kuperman, “Adjoint modeling for acoustic inversion”, *J. Acoust. Soc. Am.* (to be published in Feb. or March 2004).

[2] Paul Hursky, Michael B. Porter, Bruce Cornuelle, William Hodgkiss, and William Kuperman, “Adjoint-Assisted Inversion for Shallow-Water Environment Parameters”, in Impact of Littoral Environmental Variability on Acoustic Predictions and Sonar Performance, Eds. Nicholas G. Pace and Finn B. Jensen, Kluwer (2002).

[3] Martin Siderius, Michael B. Porter, Paul Hursky, and Peter Nielsen, Jurgen Sellshop, “Matched field processing in a highly variable shallow water site”, *J. Acoust. Soc. Am.*, **111**:2438, *Pt. 2*, 143rd Meeting, Acoust. Soc. of Am., Pittsburg, PA, FL, 3-7 June 2002.

[4] Paul Hursky, Michael B. Porter, Bruce D. Cornuelle, W. S. Hodgkiss, W. A. Kuperman, “Adjoint methods for two-dimensional inversion and error analysis”, *J. Acoust. Soc. Am.*, **112**:2402, *Pt. 2*, 144th Meeting, Acoust. Soc. of Am., Cancun, Mexico, 2-6 December 2002.